INDIAN JOURNAL OF
ENGINEERING

19(51), 2022

Variability Reduction of Electrostatic Powder Coating Process of Ceiling Fan Blades using Taguchi Methodology

Abdalla N Salih

To Cite:
Salih AN. Variability Reduction of Electrostatic Powder Coating Process of Ceiling Fan Blades using Taguchi Methodology. *Indian Journal of Engineering*, 2022, 19(51), 144-153

Author Affiliation:
Industrial Engineer, MSA University, Faculty of Engineering, Giza, Egypt
Email: abdalla.nagimeldin@msa.edu.eg

Peer-Review History
Received: 25 February 2022
Reviewed & Revised: 26/February/2022 to 02/April/2022
Accepted: 03 April 2022
Published: 05 April 2022

Peer-Review Model
External peer-review was done through double-blind method.

ABSTRACT

Consistency of Ceiling fan blades weights is essential to avoid unbalanced rotation of the fans. The unbalanced rotation of the fans can lead to poor performance, noise, and reduces the life of the final product. Variation reduction teams apply different techniques such as Design of Experiments (DOE) and robust design to enhance the efficiency and quality of the products by reducing the variability caused by production processes. This study focuses on reducing the variation in fan blades powder coating process. Taguchi method (TM) were applied on industrial setting for identifying the critical factors affecting the electrostatic powder coating process. The effect of powder coating parameters (gun stand-off distance and gun traverse speed, voltage applied and pressure) on coating thickness were studied to reduce process variability. The experiment was carried out to improve the current operating parameters. The experimental results were analyzed using Minitab 19 statistical package. Main effects plots obtained from the first experiments showed that coating thickness, the third level of voltage at 100 KV (L3), the second level of speed at 35 m/s (L2), the second level of distance at 300 mm (L2), and the first level of pressure at 2.5 bar (L1), result in improving the Standard deviation of coating thickness from 19.4 to 4.1 and the real capability of the process (Cpk) increased from a value of -0.21 to 0.52. Similarly, the process potential capability (Cp) was improved from 0.47 to 1.38. These values indicate that the electrostatic powder coating process achieved a great reduction in the variability.

Keywords: Electrostatic Powder Coating, Variability Reduction, Taguchi Methodology

1. INTRODUCTION

The statistical techniques may be useful when analyzing the effect of several machine parameters on specific characteristic. Design of Experiments (DOE's) would save resources and time through concerted efforts. The Taguchi method has established itself as an effective way for robust design in providing the process and product of high quality that are less sensitive to noise with relatively low operating costs. The goal here is to improve the

consistency of powder coating thickness with in the required film thickness. Low film thickness will result poor surface finish, on the other hand high film thickness will increase the cost of raw material.

Objectives

1. To clarify the effect of electrostatic powder coating process parameters on film thickness.
2. To find optimum levels of electrostatic powder coating process parameters that improve the consistency of thickness.

2. LITERATURE REVIEW

An electrostatic field is like a typical magnetic field, because when an object becomes charged it creates an electrostatic field. If the object has an excess in the number of its electrons, it is negatively charged. If the object has fewer electrons than its environment, it is positively charged. A part will be hanged on the hook and the powder will be charged thorough high voltage generator, then oppositely charged particles will be attracted to one another. This is the concept behind electrostatic painting [1]. The item to be painted receives a negative charge from a negatively charged electrode that works as a battery cord in electrostatic painting. The paint is charged positively and sprayed on with a spinning nozzle. The opposite charges attract the paint to the metal surface like a magnet. The paint looks out grounded objects and "wraps" itself around the painted object. Because the attraction between the opposing charges is strong, the paint will be drawn around the item and completely cover the surface. Because the paint is attracted to the metal in a static manner from all directions, there is no mess from overspray. Consider how this may work with, say, painting a wrought iron fence. The paint will be painted on and wrapped around each portion of the fence, adhering onto the backside. Here should be no mess in the surrounding area, and very little, if any, paint would be wasted because there would be no overspray. [2]

According to study applied at General Motor's powder laboratory. A powder supplier sent two shipments of powder which were formulated exactly the same. One shipment had an average particle diameter of 23 microns while the other shipment had an average particle diameter of 32 microns. Running the same test under the constant operating parameters several times gave following results as obtained in table1[3].

Table 1: The effect of particles size on coating thickness [3].

Powder size (μm)	Transfer efficiency	Avg. film thickness(mm)	Film build standard deviation.
23	**61%**	**2.4**	**0.39**
32	**64%**	**2.6**	**0.49**

W. Y. Li [4] study impact of stand-off distance (the distance between the nozzle exit and the substrate) on coating deposition characteristics was investigated, and it was discovered that the optimal stand-off distance for maximum powder deposition efficiency changes with particle velocity.

3. EXPERIMENT AND ANALYSIS

Samples measured using the current process parameters

50 samples were measured from the blades coating thickness using the old process parameters as shown in table 2.

Table 2: Current process parameters coating thickness.

SAMPLE NO	Coating film thickness in (μm)	SAMPLE NO	Coating film thickness in (μm)	SAMPLE NO	Coating film thickness in (μm)
1	87.8	19	106.0	37	75.6
2	97.6	20	103.0	38	70.6
3	86.5	21	82.3	39	76.9
4	75.6	22	81.7	40	88.7
5	79.4	23	68.3	41	75.2
6	116.0	24	68.4	42	60.6

7	122.0	25	68.4	43	63.5
8	112.0	26	67.3	44	63.1
9	95.5	27	74.8	45	76.6
10	91.2	28	78.0	46	74.3
11	99.6	29	76.2	47	78.9
12	61.9	30	122.0	48	95.9
13	60.2	31	108.0	49	80.1
14	58.4	32	105.0	50	83.7
15	93.7	33	84.0		
16	89.6	34	79.7		
17	155.0	35	77.4		
18	118.0	36	80.2		

Process capability analysis

The analysis of process capability is described as the engineering analysis to predict process capability. The process capability determines the current process capability of meeting the specifications of quality characteristic. An integrated quality assurance program should provide a process capability analysis. The potential process capability index (Cp) compares the process's approved design variations to the process's existing variation amplitude. It can be determined by dividing the width by the amplitude of the natural variation, as shown below. Where σ represents the standard deviation of the operation and (USL, LSL) are the upper specification limit and lower specification limit of the quality characteristic in the analysis. Table 3 outlines the process classes for analysis according to the Cp values.

$$Cp = \frac{\text{USL} - \text{LSL}}{6\sigma}$$

Table 3: Analysis of process capability, Cp index

Value of index	**Class**	**Results**
Cp = 2.20	World class	It has the quality of six sigma
Cp > 1.330	1	Suitable
1.0 < Cp <1.330	2	Acceptable, needs tight control
0.67 < Cp < 1.0	3	Requires significant modifications to achieve satisfactory quality
Cp < 0.67	4	Not suitable for the task. Needs serious modifications

To take into consideration the centering of the process, the real process capability index Cpk should be calculated. It could be used as an adjustment to the Cp. The Cpk value relating to Cp is a perfect indicator of how far the process operates from the center. The Cpk can be calculated through the following equation, where (USL, LSL) upper and lower specifications limits respectively, μ refer to the operation mean, σ the standard deviation.

$$Cpk = \min\left[\frac{\mu - \text{LSL}}{3\sigma}, \frac{\text{USL} - \mu}{3\sigma}\right]$$

To implement the process capacity analysis, it is necessary to show that the data follows a normal distribution. The fit test is primarily used to indicate the behavior of data. To use the above equations for process capacity indices, ensure that the electrostatic painting process follows a normal distribution. Thus, that null hypothesis is the data is normally distributed.

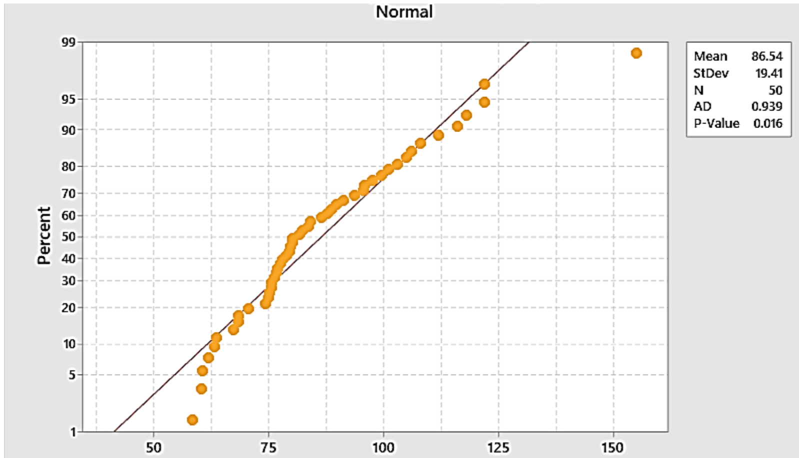

Figure 1: Probability plot of coting film thickness.

In Figure 1, the normal behavior can be observed as that data fits to the line which is represent the normal distribution. Furthermore, the p-value from Anderson-Darling test is higher than 0.005 therefore accept the null hypothesis and concludes that the data fit into normal distribution.

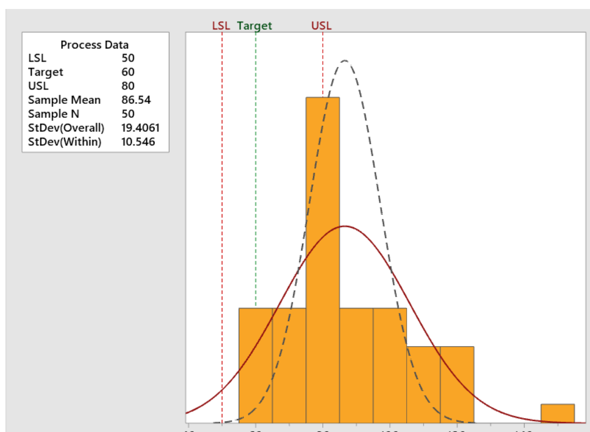

Figure 2: Process capability analysis results.

Table 4: Process capability analysis index results.

Index
Cp = 0.47
Cpk = - 0.21

Figure 2 indicates the behavior of the electrostatic painting process and table 4 shows the results for the Cp and Cpk indexes. The specifications limit of the company for the film coating thickness, lying between LSL= 50 μm and USL= 80 μm and the target = 60 μm. Over USL many samples were noticed. The process is not suitable for the job according to the potential process capacity index value result (Cp=0.47). Significant modifications are essential to ensure the needed specifications. In addition to this, as this value is higher than the actual process capacity index (Cpk= -0.21), it could be noticed that the process is not centered as shown in Figure 1, that indicates that the mean of painting process is found away from the specification center, and there is a high probability of producing units higher than the thickness of the upper specification limits.

Selection of the controlled parameters

When preparing to experiment, it is important to choose the parameters that most likely to affect the quality characteristic to be improved. The controlled parameters are parameters that can be identified and controlled during the experiment the four selected parameters are shown in figure 3 and current values of them are shown in table 5.

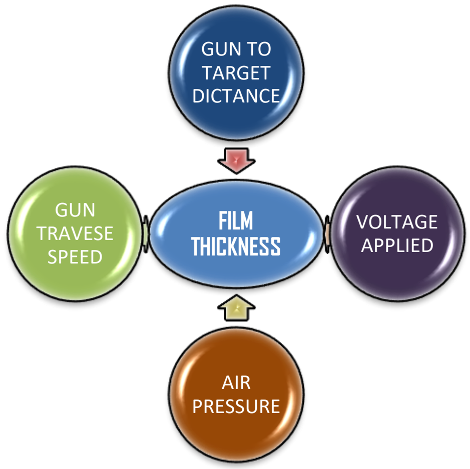

Figure 3: Process controlled parameters.

Table 5: Current process parameters values.

Parameter	Voltage (kV)	Gun Speed (mm/ s)	Gun Distance (mm)	Air Pressure (bar)
Value	80	300	190	4

The levels of parameters are different values of each parameter that is going to be tested during the experiment to determine how these parameters interact with each other during the experiment and their effect on the response. Number of levels depends on the process behavior and the availability of trails. It is preferred to have at least three process parameters levels to represent the true behavior of the study output parameters. Thus, three levels have been assigned to the control parameters as shown in Table 6.

Table 6: Process parameters levels

Process Parameter	**Levels**		
	L1	**L2**	**L3**
Voltage (kV)	80	90	100
Gun speed (mm/s)	25	35	45
Gun to target distance (mm)	200	300	400
Pressure (bar)	2.5	3.5	4.5

Table 7: Taguchi orthogonal arrays

	Parameters			
Trails	**Voltage (kV)**	**Speed (mm/s)**	**Distance (mm)**	**Pressure (bar)**
1	**80**	**25**	**200**	**2.5**
2	**80**	**35**	**300**	**3.5**
3	**80**	**45**	**400**	**4.5**
4	**90**	**25**	**300**	**4.5**
5	**90**	**35**	**400**	**2.5**
6	**90**	**45**	**200**	**3.5**

7	100	25	400	3.5
8	100	35	200	4.5
9	100	45	300	2.5

Orthogonal arrays represent the minimum number of trails, containing the different combination of factors. The output of the orthogonal arrays is tested for the signal-to - noise ratio (S/N) of the responses rather than the responses themselves and thus the process variability reduced. Taguchi orthogonal array is designed with the assistance of Minitab 19 software as shown in table 6 with three levels of four parameters the Minitab is shown in table 7.

To perform the experiment as per designed 40 samples used for each condition and the coating thickness is measured as shown in table 8, the setup is performed as shown in following figures 4 and 5 The setup producer of changing the machine parameters as selected before in figure 3 to the levels as per Taguchi array guide in table 5 while other process parameters remain constant. From figure 4 which shows the machine interface the voltage applied and the pressure changed to the desired value and from figure 5 the gun speed and the gun stand-off distance are changed.

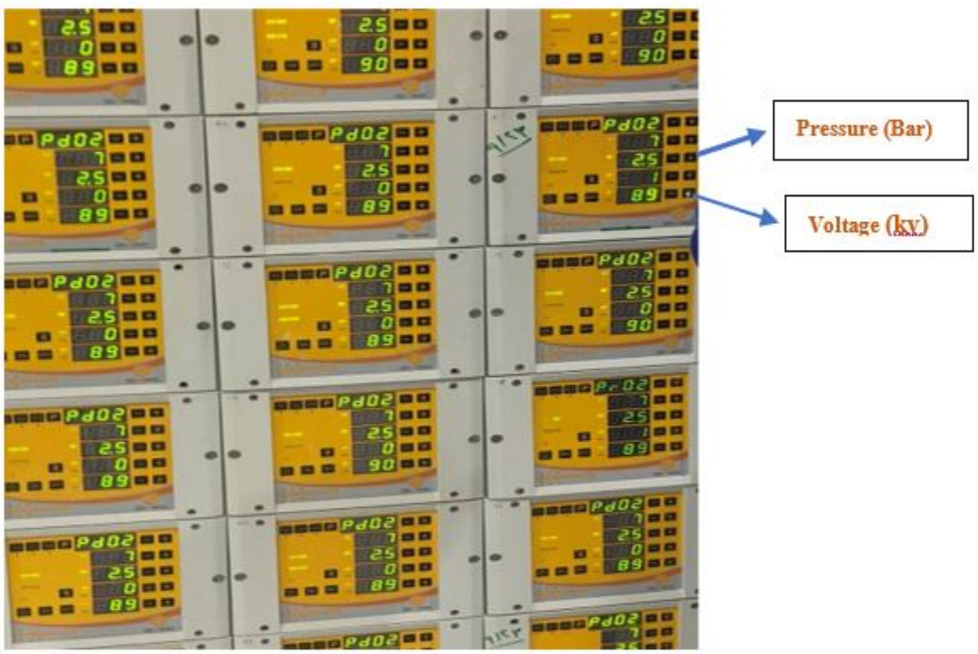

Figure 4: Voltage and pressure setup.

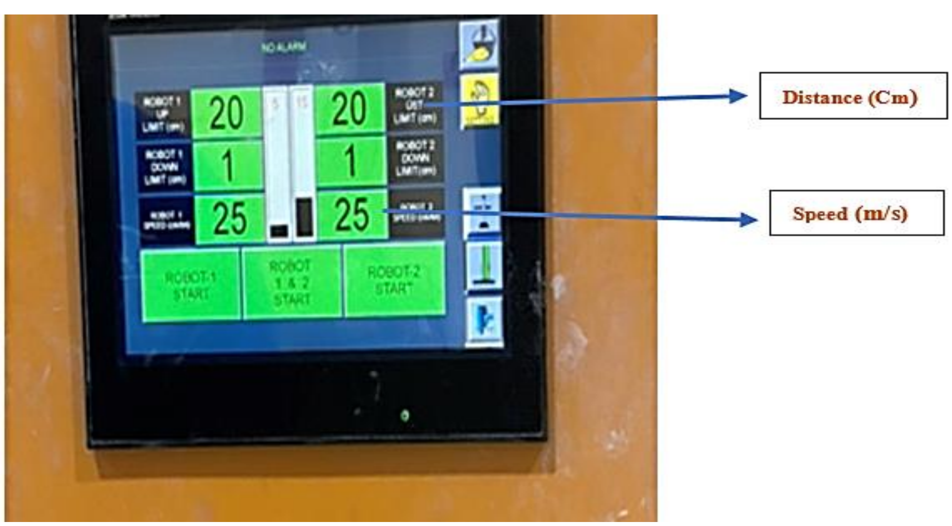

Figure 5: Distance and speed setup

4. RESULTS AND DISCUSSION

The coating thickness measured for after the implementation of the experiment for each operating condition the results are shown in table 8 below.

Table 8: Coating Film Thickness (μm).

Sample No	Trails No								
1	88	60	39	66	61	40	42	60	60
2	76	59	35	72	64	38	40	52	74
3	87	62	37	70	68	37	40	54	69
4	82	55	30	61	64	30	48	63	73
5	73	48	30	60	54	55	46	55	73
6	77	51	28	65	55	59	46	56	83
7	68	52	58	67	61	27	42	59	71
8	88	52	60	68	56	14	54	52	77
9	80	51	64	65	61	15	46	60	63
10	78	58	53	69	60	22	43	68	73
11	76	64	64	65	61	25	47	55	76
12	75	55	62	72	68	32	43	55	80
13	74	58	56	62	57	25	44	63	67
14	72	53	64	61	58	18	52	61	78
15	81	54	66	68	58	29	47	63	74
16	85	57	58	63	54	29	46	61	75
17	74	53	67	65	59	28	45	59	74
18	73	62	63	70	55	45	44	60	80
19	75	59	63	65	58	17	48	65	85
20	77	54	70	64	61	21	44	61	77
21	75	59	58	71	58	41	42	59	67
22	79	46	53	65	68	31	47	57	74
23	75	52	60	59	68	39	50	60	69
24	79	54	60	59	61	41	45	59	61
25	80	55	63	66	59	41	39	55	74
26	80	56	64	63	66	48	43	56	73
27	84	53	64	61	71	43	46	60	68
28	84	56	60	58	67	46	43	59	62
29	79	54	54	56	62	31	43	58	63
30	87	53	63	62	65	32	44	57	69
31	84	51	60	69	56	49	46	57	65
32	88	66	65	63	55	49	44	65	63
33	88	58	60	67	59	52	43	62	77
34	79	56	65	64	57	45	47	65	71
35	79	56	56	61	62	49	48	58	72
36	80	54	61	61	68	52	50	67	71
37	78	54	67	59	62	42	27	58	75
38	84	60	65	68	68	42	45	60	77
39	86	56	64	57	68	52	40	62	69
40	86	61	68	58	57	41	47	67	73

There are four factors, each factor has three stages. As a result, the suitable orthogonal array to be conducted is L9, as shown in table 7. There are nine experimental runs in this orthogonal array, each run has 40 samples. The means of each treatment are used in the statistical study of the orthogonal array. The results are shown in this table 8.

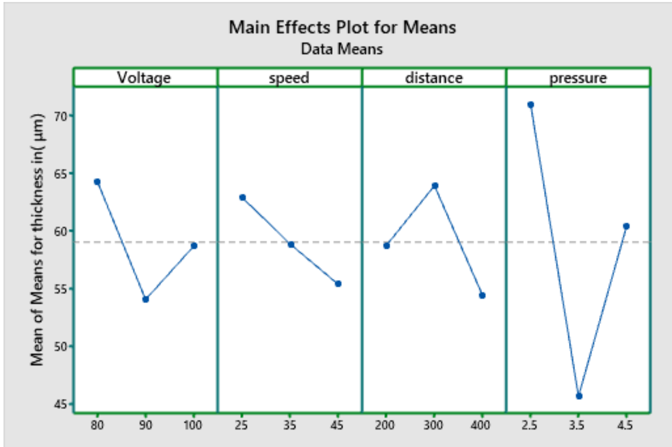

Figure 6: Main effects plots for coating thickness versus voltage, gun traverse speed, gun stand- off distance and pressure.

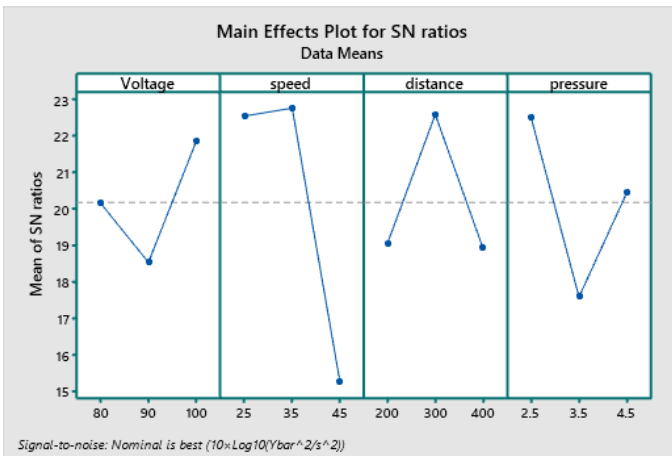

Figure 7: Main effects plots for SN ratio versus voltage, gun traverse speed and gun stand- off distance and pressure.

The blades were examined after coating and curing. At 200 mm distance it observed less and non-uniform coating thickness than the 300 mm as shown in figure 6 and 7. This is due to the powder fall, as it fails to get attracted towards the blades. The explanation for this is that the first layer of powder deposited on the blade surface repels further layers of powder. At 400 mm stand-off distance, the powder does not cover the entire blade surface, and the coating thickness is very thin. This will expose the coating to the environment even further, and the coating's function will be defeated. The explanation for this is that gravity causes powder particles to take a downward trajectory rather than a straight path

It is also observed in figure 6 that the dry film thickness decreases with increasing the pressure but it slightly increases again, because at moderate pressure values the pressure become high enough to disperse the powder away from the blades but not to concentrate the powder on the blades. Figure 7 shows that the uniform coating thickness is observed at 2.5 bar pressure value as the noise is at its lowest value.

Figure 7 shows that the SN ratio increase with the increase in the applied voltage and then return to decrease on the other hand, the coating thickness decreases at 90 kV and then returns to increase at 100 kV, this is mainly because at 90 kV as shown in figure 6 the noise effect increases, which means that the operating conditions done at relatively high noise environment.

It also observed that the faster gun velocity, the lower mean of dry film thickness, very high values as shown in figures 6 and 7. Therefore, it is preferred to operate at a lower velocity to provide a better control of the painting process.

Improving the operating parameters

Table 9: Response table for means

Level	Voltage	Speed	Distance	Pressure
1	64.31	62.87	58.73	70.98
2	54.06	58.83	63.89	45.71
3	58.70	55.37	54.44	60.38
Delta	10.25	7.50	9.45	25.27
Rank	**2**	**4**	**3**	**1**

The ranks in Table 9 are based on delta statistics, which comparing the magnitudes of the effects. For each factor, the delta statistics is the highest minus the lowest average. Minitab gives ranks according on delta values; the highest delta value is ranked 1, the second highest is ranked 2, and so on. The relative importance of each factor to the response is indicated by the ranks. Powder flow rate has the highest effect on weight, followed by voltage, speed, distance, and pressure in that order, according to the ranks and delta values for various parameters. Based on previous analysis it can be concluded that the third level of voltage at 100 KV (L3), the second level of speed at 35 m/s (L2), the second level of distance at 300 mm (L2), and the first level of pressure at 2.5 bar (L1), thus the result in improving the uniformity of coating thickness.

Confirmation experiment

To examine the standard deviation and the process capability conducted before, a second process capability analysis was conducted for the electrostatic painting. Under the new operating conditions, the analysis of process capability results shown in Figure 8. While investigating, 40 samples were taken from the electrostatic painting process, the results shows that the process's real capability of the (Cpk) increased from a value of -0.21 to 0.52. The process potential capability (Cp) was also improved, and achieved a result of 1.38. These results indicate that the electrostatic painting process is now suitable, has better centering than the previous process and capable to meet specifications. Therefore, the results show that centering the process is possible and that the variability was reduced. The reduction of process variability was done by setting the process parameters.

Based on the experimental results, the standard deviation decreased from 19.4 to 4.17 as by using the selecting new parameters The real capability of the process (Cpk) increased from a value of -0.21 to 0.52. Similarly, the process potential capability (Cp) was improved, and it achieved a value of 1.38 as shown in table 10.

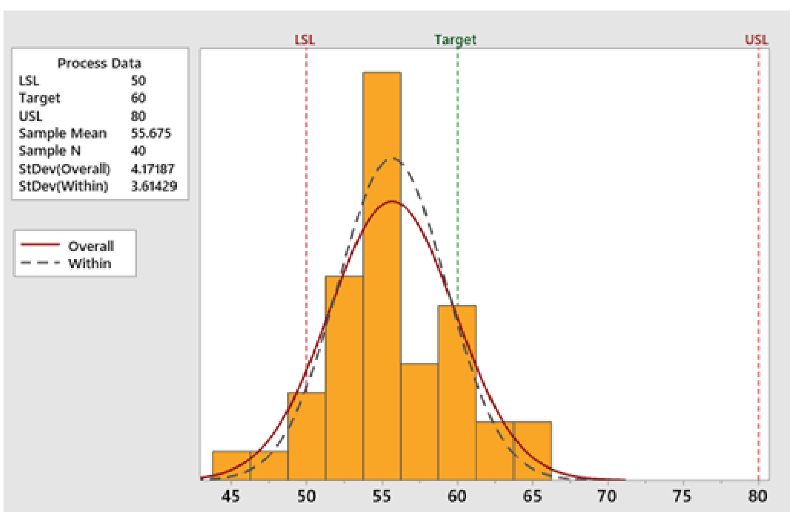

Figure 8: process capability after the change in parameters

Table 10: Process capability analysis index results.

Index
Cp = 1.38
Cpk = 0.52

5. CONCLUSION

The research was focuses on improving the consistency of coating thickness by improving the operating parameters of the electrostatic coating process. The effect of the parameters on the coating thickness and the capability of the process were studied. The experimental results were analyzed using Minitab 19, statistical software, to study the effect of process parameters in response variables. Main effects plots obtained from the first experiments showed that coating thickness, the third level of voltage at 100 KV (L3), the second level of speed at 35 m/s (L2), the second level of distance at 300 mm (L2), and the first level of pressure at 2.5 bar (L1), showing less level of noise effect. The selected parameters result in improving the standard deviation of coating thickness in the confirmation experiment from 19.4 to 4.17. The process capability analysis was established using the new parameters and compared to the values obtained before. The real capability of the process (Cpk) increased from a value of -0.21 to 0.52. Similarly, the process potential capability (Cp) was improved, and it achieved a value of 1.38. These values indicate that the electrostatic painting process is now suitable, has better centering than the previous process and capable to meet the required specifications.

Funding

This study has not received any external funding.

Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. J. Domnick, A. Scheibe, Q. Ye. The simulation of the electrostatic spray painting process with high-speed rotary bell atomizers, Part I: Direct charging. Part. Part. Syst. Charact. 2005, 22, 141–150.
2. Gasparetto, R. V. Pillan, and E. Saccavini, "Automatic path and trajectory planning for robotic spray painting," in Proceedings of the 7th German Conference on Robotics, pp. 211–216, Munich, German, 2012.
3. James Edward Beuerle, Jr. "A Study of Electrostatically Applied Powder Paint in the Automotive Industry", (1992), Purdue University, pp.55–70.
4. W.-Y. Li, C. Zhang, X.P. Guo, G. Zhang, H.L. Liao, C.-J. Li, C. Coddet, "Effect of standoff distanceon coating deposition characteristics in cold spraying", Materials and Design, 29 (2008) 297–304.